

Interpretation of Mariner 5 and Venera 4 Data on the Upper Atmosphere of Venus

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ABSTRACT

Calculations have been completed on the structure of the ionosphere of Venus. Comparisons between these calculations and the results of the Mariner 5 and Venera 4 flights yield the following information on the structure of the Venus upper atmosphere: the ionosphere of Venus is of the F₁ type; no more than 2% of the CO₂ in the Venus ionosphere is dissociated; the relative abundance of N₂ is $\leq 10\%$, in rough agreement with the Venus 4 limit of 7%; the exospheric temperature is $700 \pm 100\text{K}$, the uncertainty in this result reflecting uncertainties in the CO₂ vibrational deactivation coefficient and heating efficiency.

1. Introduction

Prior to the flights of Mariner 5 and Venera 4 past Venus in October 1967 there was little concrete information regarding that planet's upper atmosphere and ionosphere. The occultation of Regulus (deVaucouleurs and Menzel, 1960) provided a single reliable datum on density in the atmosphere above the clouds. Spectroscopic observations indicated the presence of CO₂ (Adams and Dunham, 1932) and the possible presence of CO (Sinton, 1963), O₂ (Prokofyev and Petrova, 1963), and water vapor (Bottema *et al.*, 1965) in the Venus atmosphere, but none of the abundances were accurately determined.

A theoretical computation of the upper atmosphere temperature had been carried out by Gross *et al.*¹ for a variety of compositions. These authors concluded that the exospheric temperature might range from 700 to 3000K, depending on the assumed abundance of CO₂. Models for the composition of the upper atmosphere were presented by Shimizu (1963). He concluded that CO₂ in the Venus upper atmosphere would be almost completely dissociated. This conclusion rested on an assumed three-body recombination mechanism for reformation of CO₂ ($\text{CO} + \text{O} + \text{M} \rightarrow \text{CO}_2 + \text{M}$). The measured rate for this three-body recombination (Marmo and Warneck, 1961) leads to the expectation of complete CO₂ photodissociation above an altitude at which the CO₂ number density is about 10^{13} cm^{-3} .

2. Summary of Mariner 5 ionosphere data and Venera 4 lower atmosphere data

Mariner 5 returned data on the ionosphere of Venus as well as on the neutral densities and temperatures at

lower altitudes (Kliore *et al.*, 1967). The observed electron density profile exhibits several striking features. Its peak density is about $5 \times 10^6 \text{ cm}^{-3}$, which is close to peak densities observed in the earth's ionosphere, but the altitude of this peak is surprisingly low, being 82 km above the point at which Mariner 5 indicates a pressure of 1 atm. In the earth's atmosphere, by contrast, the E, F₁ and F₂ layers are at altitudes of about 110, 180 and 250 km, respectively. The Venus ionosphere is also narrow, the half-width being about 20 km in contrast to a half-width of about 100 km for the earth's ionosphere.

Venera 4 returned information on the composition, pressure and temperature of the lower atmosphere, which are important for the present discussion of ionospheric properties. A summary of the composition data is shown in Table 1.

TABLE 1. Venera 4 reported composition of Venus atmosphere (Vinogradov *et al.*, 1968).

Constituent	Abundance
CO ₂	$90 \pm 10\%$ (probably more than 90%)
O ₂	0.4–1.6% (probably $\approx 1\%$)
N ₂	$< 7\%$ (probably $< 2.5\%$)
H ₂ O	from 1–8 mg liter ⁻¹

3. Details of the theory

The electron and ion densities for the Venus ionosphere models are obtained by solution of the rate equations corresponding to the reactions listed in Table 2. The CO₂⁺ dissociative recombination rate is most important in these calculations. This was taken as $3.3 \times 10^{-7} \text{ cm}^3 \text{ sec}^{-1}$, at the lower end of the range given

¹ Gross, S. H., W. E. McGovern and S. I. Rasool, 1967: On the exospheric temperature of Venus. Paper presented at the Conference on Atmospheres of Mars and Venus, 27 February–2 March 1967, Tucson, Ariz.

TABLE 2. Reactions and reaction rates appropriate to the ionosphere of Venus.

Reactions	Rates (cm ³ sec ⁻¹)	
Dissociative recombination		
CO ₂ ⁺ +e ⁻ →CO+O	(3.8±.5)×10 ⁻⁷	(W)
O ₂ ⁺ +e ⁻ →O+O	(1.7±1)×10 ⁻⁷	(B)
N ₂ ⁺ +e ⁻ →N+N	2.8×10 ⁻⁷	(B)
NO ⁺ +e ⁻ →N+O	5.0×10 ⁻⁷	(B)
Charge exchange		
CO ₂ ⁺ +O ₂ →CO ₂ +O ₂ ⁺	1.0×10 ⁻¹⁰	(N)
CO ⁺ +CO ₂ →CO+CO ₂ ⁺	1.1×10 ⁻⁹	(N)
CO ⁺ +O ₂ →CO+O ₂ ⁺	2.0×10 ⁻¹⁰	(N)
N ₂ ⁺ +O ₂ →N ₂ +O ₂ ⁺	1.0×10 ⁻¹⁰	(N)
N ₂ ⁺ +CO ₂ →N ₂ +CO ₂ ⁺	8.0×10 ⁻¹⁰	(N)
Ion-atom interchange		
O ⁺ +CO ₂ →CO+O ₂ ⁺	1.2×10 ⁻⁹	(N)
O ⁺ +O ₂ →O+O ₂ ⁺	3.5×10 ⁻¹¹	(N)
O ⁺ +N ₂ →N+NO ⁺	1.8×10 ⁻¹²	(N)
N ₂ ⁺ +O→N+NO ⁺	2.5×10 ⁻¹⁰	(N)

(B) Biondi, 1964; (N) Norton *et al.*, 1966; (W) Weller and Biondi, 1967.

by Weller and Biondi (1967). Higher values give somewhat poorer agreement between the calculated and observed electron densities.

The calculations give both the thermal structure and the ionospheric profile. Static conditions ($d/dt=0$) were assumed for all species. The solar zenith angle was taken as 33° to correspond to that of the Mariner 5 dayside ionosphere observation. The solar flux data of Hinteregger *et al.* (1965) were used; these were adjusted to the orbit of Venus and to the period of the solar cycle corresponding to Mariner 5 observation. The CO₂ photoionization cross sections were taken from Cook and Ching (1965) and Schultz *et al.* (1963). Cross sections for N₂ and O₂ are from Hinteregger *et al.* (1965).

Neutral densities are obtained by integration of the hydrostatic balance equations above some reference point in the atmosphere. This point was taken at 6106 km from the planetary center, where the pressure is 1 atm. The temperature between 6106 and 6130 km was chosen to replicate the dayside temperature profile based on Mariner 5 observation of the neutral atmosphere. The original altitude scale given by Kliore *et al.* (1967) is used in these calculations. The results will not be affected by shifts in this scale.

The upper atmosphere temperature is calculated by solution of the thermal conduction equation, with inclusion of radiative losses by CO₂, CO and O. The CO and O cooling terms are those provided by the Bates approximation (Bates, 1951). The CO₂ cooling term is given by Chamberlain and McElroy (1966). The solar ultraviolet heating and ion production functions are obtained by a summation over the 68 wavelength intervals and flux lines given in Hinteregger *et al.* (1965). The procedure is iterative, temperatures and densities being

successively recalculated until consistent results are obtained.

4. Results

a. Thermal structure. Integration of the thermal conduction equation is begun near the mesopause with an assumed boundary temperature and initial gradient.

The starting altitude was chosen as the mesopause, i.e., the altitude at which the ultraviolet heating being conducted downward had been radiated away by cooling in the 15 μ CO₂ band, so that the temperature gradient was zero. This consideration fixes the starting point at 6180 km, with an uncertainty of about 12 km.

There is a gap of about 50 km between the highest Mariner 5 data at 6130 km and the starting point of these integrations in the neighborhood of 6180 km. Appropriate starting temperatures for the integration were obtained by bridging the gap with two models designed to represent limits of plausible assumptions for the unknown region. In one, an isothermal regime connects the Mariner 5 temperature of 230K at 6130 km to the start of the present integration; in the other, the Mariner 5 lapse rate of 2K km⁻¹ is extrapolated upward from 6130 km to the starting altitude.

The temperatures calculated in the upper thermosphere and exosphere were insensitive to the choices of starting altitude, temperature, and temperature gradient with the ranges described above. The variation in computed exospheric temperature for this range of boundary conditions was typically about 5K, all other parameters being fixed.

The exospheric temperature is, however, sensitive to variations in the vibrational deactivation coefficient of

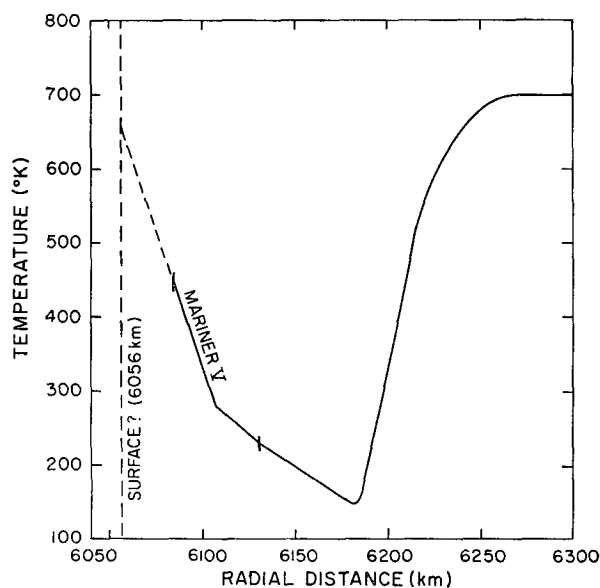


FIG. 1. Temperature profile obtained by varying parameters of the model to secure agreement with the combination of atmospheric data and ionospheric data yielded by Mariner 5.

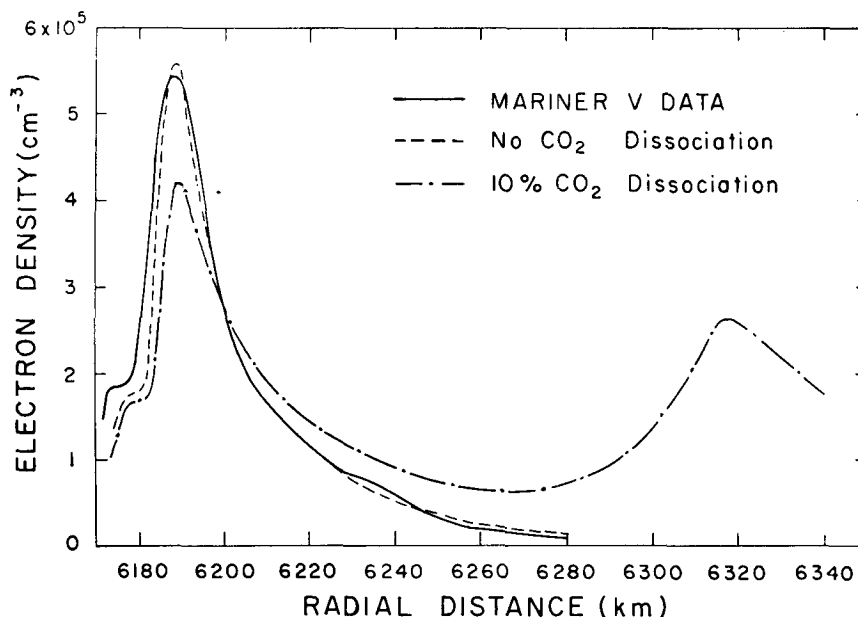


FIG. 2. Model ionospheres (dashed curves) for assumed degrees of CO_2 dissociation at 6170 km. The solid curve is the ionosphere observed by Mariner 5.

CO_2 and the heating efficiency. The vibrational deactivation coefficient is strongly affected by the presence of hydrogen compounds (Lambert, 1962; McElroy, 1968). The fractional abundance of such constituents in the Venus thermosphere is unknown. There is also substantial uncertainty of the order of 30% in the heating efficiency. These uncertainties correspond to a probable error of $\pm 100\text{K}$ in the calculated exospheric temperature.

The uncertainties in the temperature and temperature gradient in the gap between 6130 and 6180 km cannot be resolved by comparison with the currently available atmospheric data. However, some additional information can be obtained by comparison with the Mariner 5 electron density profile, whose altitude of peak ionization turns out to be rather sensitive to the temperatures in the intermediate region. The isothermal model produces a peak altitude of ionization about 20 km too high, and the straight extrapolation of the 2K km^{-1} temperature gradient produces an altitude about 5 km too low. The best results are obtained with a temperature gradient of 1.6K km^{-1} , and a mesopause temperature of 145K , the resulting temperature profile being shown in Fig. 1.

b. CO_2 dissociation. Data from Venera 4 and indirect information from Mariner 5 indicate that CO_2 is the principal constituent of the Venus atmosphere. CO_2 is dissociated by radiation of wavelength less than 1750\AA . Since CO_2 is present in abundance in the Venus atmosphere, there must be some mechanism by which the dissociation products recombine to form CO_2 . Studies of the upper atmosphere composition of Venus (Shimizu, 1963) have been based on the assumption that three-

body recombination ($\text{CO} + \text{O} + \text{M} \rightarrow \text{CO}_2 + \text{M}$) is the appropriate mechanism. This reaction is slow, leading to essentially complete dissociation of CO_2 down to an altitude at which the CO_2 number density is approximately 10^{13} cm^{-3} . This density occurs at about 6170 km in the model atmospheres used in these studies.

In highly dissociated models, one of the dissociation products O becomes the dominant constituent in the upper atmosphere since it is a much lighter gas than CO_2 and has a correspondingly larger scale height. This is analogous to the situation on the earth where photodissociation of O_2 leads to a broad layer in which O is the dominant constituent. Venus ionospheres calculated for highly dissociated models exhibit extensive ionization between 6300–6350 km with a peak at the altitude where the photochemical and diffusive lifetimes are equal.

The Mariner 5 data do not show the predicted electron densities at high altitudes. According to these data, electron densities on Venus fall off more rapidly with increasing altitude than would be expected if O formed from CO_2 dissociation were present.

The effect of CO_2 dissociation on the calculated electron density profile is shown in Fig. 2. The solid curve in this figure is the ionosphere observed by Mariner 5. The other two curves are model ionospheres computed for an assumed neutral composition of 99% CO_2 and 1% N_2 , and for 0% and 10% dissociation of CO_2 at 6170 km. The undissociated model of Fig. 1 is in better agreement with observation. The neutral density at the peak in this model is $1.8 \times 10^{11}\text{ cm}^{-3}$ and the temperature 192K . It has been found in these studies that an F_2 peak is formed at high altitude whenever more than 2% dissociation of CO_2 is assumed at 6170 km.

The results concerning the degree of CO_2 dissociation are based on an assumed turbopause 10 km above the dissociation level. A higher turbopause would increase the suggested limits. However, if the CO_2 photochemistry involves a loss rate which decreases appreciably faster with altitude than does the dissociation rate, then one expects a fairly sharp dissociation level. The inconsistency between observed and calculated ionospheric profiles introduced by a small degree of CO_2 dissociation at 6170 km indicates that the three-body recombination mechanism is not relevant in the Venus atmosphere.

McElroy (1967) has suggested an alternate recombination mechanism involving a collision of $\text{O}(^1\text{D})$ with CO_2 to form an intermediate CO_3 complex which then undergoes collision with CO to re-form CO_2 . This recombination mechanism implies that CO_2 dissociation will occur at high altitude, since the loss rate falls off with altitude more rapidly than the dissociation rate. Models were studied in which 90% CO_2 dissociation was assumed at various altitudes. The results of this study indicate that the dissociation level must be above 6250 km in the Venus atmosphere.

It should be noted that the UV photometer search for O carried out by Mariner 5 may place a stricter limit on the degree of photodissociation of CO_2 than the limit provided by the ionosphere calculations.

c. N_2 content. The limit on CO_2 dissociation implies that the Venus ionosphere is of the F_1 rather than the F_2 type. F_1 models with various N_2 abundances have been studied to obtain information on the N_2 content. A substantial amount of N_2 broadens the ionosphere profile and correspondingly lowers the peak electron density because its molecular weight is smaller than that of CO_2 and its scale height greater. The results shown in Fig. 3 suggest that the N_2 abundance is 10% or less, in rough agreement with the Venera 4 upper limit of 7%. For greater N_2 abundances the half-width is too large and the peak density too small to agree with the Mariner 5 data. The best agreement with the observations is obtained for models containing 0–2% N_2 .

The models in Fig. 2 were computed on the assumption that CO_2 and N_2 were mixed throughout the ionosphere. The assumption of diffusive separation would place more stringent limits on the N_2 content.

N_2^+ will not constitute an important component in the ionosphere because it is rapidly converted to CO_2^+ by $\text{N}_2^+ + \text{CO}_2$ charge exchange (Table 2).

d. O_2 content. The present models are sensitive to the O_2 abundance because photodissociation of O_2 in the upper atmosphere releases O, leading to formation of a terrestrial-type F_2 layer in the Venus ionosphere. These calculations permit a rough limit of 1.0% to be placed on the abundance of O_2 . The spectroscopic limits are smaller. Spinrad and Richardson (1964) give an upper limit of 8×10^{-5} on the fractional abundance of O_2 and Belton *et al.* (1968) give 4×10^{-5} .

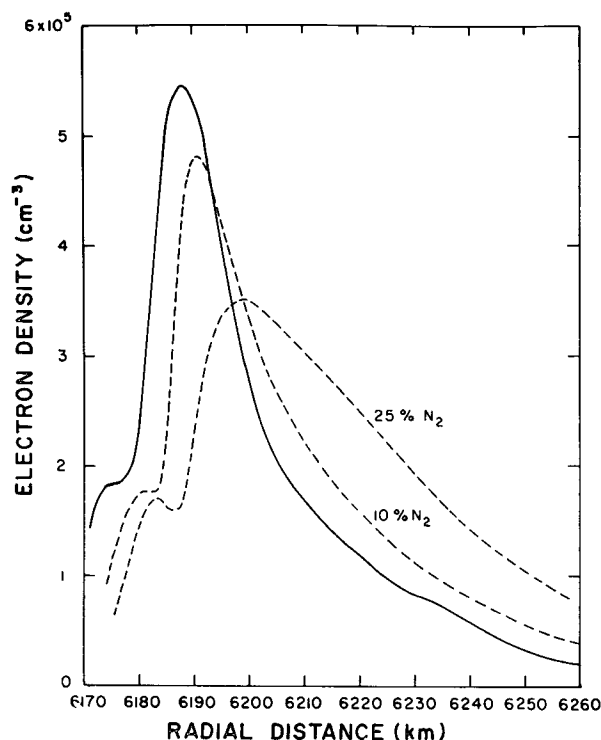


FIG. 3. Model ionospheres (dashed curves) for 10% and 25% assumed N_2 abundances. The solid curve is the ionosphere observed by Mariner 5.

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